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**EXPERIMENTAL AND MATHEMATICAL ANALYSIS OF  
MULTILAYER INSULATION BELOW 80 K**

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**Abstract**

The Large Hadron Collider [1], presently under construction at CERN, will make an extensive use of multilayer insulation system (MLI). The total surface to be insulated will be of about 80000 m<sup>2</sup>. A mathematical model has been developed to describe the heat flux through MLI from 80 K to 4.2 K. The total heat flux between the layers is the result of three distinct heat transfer modes: radiation, residual gas conduction and solid conduction. The mathematical model enables prediction of MLI behavior with regard to different MLI parameters, such as gas insulation pressure, number of layers and boundary temperatures. The calculated values have been compared to the experimental measurements carried out at CERN. Theoretical and experimental results revealed to be in good agreement, especially for insulation vacuum between 10<sup>-5</sup> Pa and 10<sup>-3</sup> Pa.

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# Experimental and Mathematical Analysis of Multilayer Insulation below 80 K

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The Large Hadron Collider [1], presently under construction at CERN, will make an extensive use of multilayer insulation system (MLI). The total surface to be insulated will be of about 80000 m<sup>2</sup>. A mathematical model has been developed to describe the heat flux through MLI from 80 K to 4.2 K. The total heat flux between the layers is the result of three distinct heat transfer modes: radiation, residual gas conduction and solid conduction. The mathematical model enables prediction of MLI behavior with regard to different MLI parameters, such as gas insulation pressure, number of layers and boundary temperatures. The calculated values have been compared to the experimental measurements carried out at CERN. Theoretical and experimental results revealed to be in good agreement, especially for insulation vacuum between 10<sup>-5</sup> Pa and 10<sup>-3</sup> Pa.

## 1 INTRODUCTION

To minimize the distributed heat transfer in a cryogenic system from 80 K to 4 K under degraded vacuum condition, the use of MLI system becomes indispensable. MLI consists of low emissivity foils alternated with a low-conductivity spacer material. The heat flux through MLI is determined by several parameters as it is the combination of three heat transfer modes, such as thermal radiation, residual gas conduction and solid conduction.

The paper presents the mathematical model developed to describe the MLI behaviour considering a layer-to-layer approach. The mathematical model has been written by using a C++ code and is based on an electrical analogy, in which the three heat transfer modes are treated as parallel thermal impedances. The values of each of the transfer mode vary from layer to layer, although the total heat transfer remains constant across the whole MLI blanket.

## 2. MATHEMATICAL MODEL

The thermal network showing the different heat transfer modes is shown in Figure 1. Radiative heat transfer ( $Q_{rad}$ ) depends on the foil emissivity  $\epsilon$ , which varies with a surface quality and is a function of the temperature. The dependence of the emissivity on temperature is given in literature by empirical correlations [2,3]. In the mathematical model, the emissivity is assumed to be proportional to the square root of the foil temperature. Radiation from layer to layer is expressed as follows:

$$Q_{rad_{i+1 \rightarrow i}} = \sigma \cdot A_i \cdot F(\epsilon_{i+1}, \epsilon_i, A_{i+1}, A_i) \cdot (T_{i+1}^4 - T_i^4) \quad (1)$$

where  $A$  is the lateral area of the foil [m<sup>2</sup>],  $\sigma$  is the Boltzmann's constant,  $F$  is the view factor and  $\epsilon$  is equal to  $0.0035 (T)^{0.5}$ .

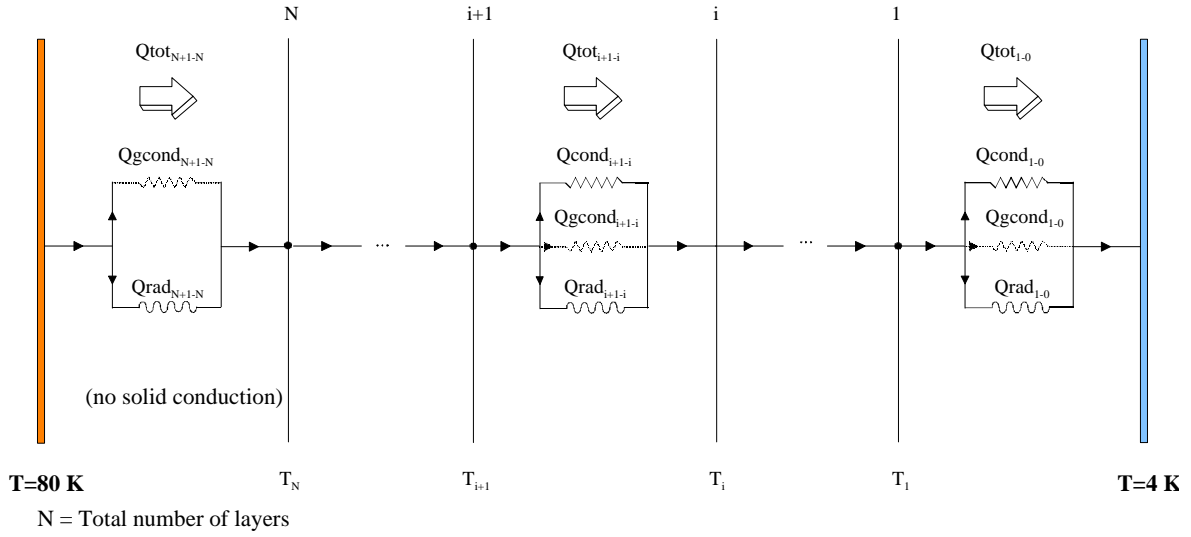


Figure 1 Thermal network of MLI systems.

Solid conduction ( $Q_{cond}$ ) depends on the heat conductivity of the spacer material, as well as its geometrical structure and temperature. For standard spacer materials, the value of heat conductivity varies from  $1 \cdot 10^{-6}$  to  $1 \cdot 10^{-3}$  W/m·K. An exact analysis has also to take into account impedances of thermal contacts in between layers. The equation describing the process is:

$$Q_{cond_{i+1 \rightarrow i}} = \frac{k_s}{t} \cdot (T_{i+1} - T_i) \quad (2)$$

where  $t$  is the spacer thickness [m] and  $k_s$  is the effective spacer conductivity [W·m/K].

Residual gas conduction ( $Q_{gcond}$ ) is described by Corrucini relation [4]. Considering two cylindrical surfaces, we obtain:

$$Q_{gcond_{i+1 \rightarrow i}} = A_i \cdot \alpha \cdot \left( \frac{\gamma+1}{\gamma-1} \right) \cdot \left( \frac{R}{8 \cdot \pi} \right)^{0.5} \cdot \frac{P}{(M \cdot T)^{0.5}} \cdot (T_{i+1} - T_i) \quad (3)$$

where  $\alpha$  is the accomodation factor,  $A$  is the lateral area [ $\text{cm}^2$ ],  $R$  is the gas constant,  $M$  is the molecular weight [g/mol],  $T$  is the absolute temperature and  $P$  is the residual gas pressure [mmHg].

In steady-state condition the total heat transfer ( $Q_{tot}$ ) from layer to layer remains constant and a set of  $(i+1)$  equations can be written:

$$Q_{tot_{i+1 \rightarrow i}} = Q_{rad_{i+1 \rightarrow i}} + Q_{cond_{i+1 \rightarrow i}} + Q_{gcond_{i+1 \rightarrow i}} \quad (4)$$

where  $Q_{cond}$  is zero from the shield at 80 K to the outer MLI layer.

By solving the set of  $(i+1)$  equations for given boundary conditions, we obtain the temperature of each layer ( $T_i$ ) and the corresponding values of heat transfer modes ( $Q_{rad_i}$ ,  $Q_{cond_i}$ ,  $Q_{gcond_i}$ ).

### 3 EXPERIMENTAL SET UP

A vertical cryostat was used at CERN to measure the heat flux through an MLI sample. This sample [4] was composed of a 10-foil blanket of double aluminised Mylar (DAM) plus 10 spacers (Lydall cryotherm 233 type). The dedicated test cryostat is composed of two screens at 80 K and 4.2 K (see Figure 2a). The outer screen is actively cooled with  $\text{LN}_2$ . In addition, two internal circuits cool the inner screen at 4.2 K. One of these circuits cools the top guard, which works as a shield for radiation from 80 K, and the other cools the lateral part of the cylinder where the sample is positioned. The measurements were performed when steady-state conditions were reached. By measuring the helium boil-

off at atmospheric pressure under different insulation vacuum conditions (obtained by degrading successively the insulation vacuum with helium gas injected into the cryostat), the heat inleaks through MLI from 80 K to 4.2 K were calculated as shown in equation 5:

$$\dot{q} = \frac{L_{\text{He}} \cdot V_{\text{NTP,GHe}} \cdot \rho_{\text{NTP,GHe}}}{A_T} \cdot \left( \frac{\rho_{\text{LHe}}}{\rho_{\text{LHe}} - \rho_{\text{GHe}}} \right) \quad (5)$$

where  $L_{\text{He}}$  is the helium latent heat at atmospheric pressure [J/kg],  $V_{\text{NTP,GHe}}$  is the measured volumetric flow at normal temperature and pressure conditions (NTP) [ $\text{m}^3/\text{s}$ ],  $\rho_{\text{NTP,GHe}}$  is the helium specific mass at NTP conditions [ $\text{kg}/\text{m}^3$ ],  $A_T$  is the total area covered with MLI [ $\text{m}^2$ ],  $\rho_{\text{LHe}}$  is the saturated liquid helium specific mass [ $\text{kg}/\text{m}^3$ ] and  $\rho_{\text{GHe}}$  is the saturated gaseous helium specific mass [ $\text{kg}/\text{m}^3$ ], both at atmospheric pressure.

#### 4. RESULTS AND DISCUSSION

The experimental and calculated results are presented in Figure 2b, where the heat flux is given as a function of residual gas pressure. They revealed to be in good agreement, especially below  $10^{-3}$  Pa. At lower residual gas pressure the heat transfer by gas conduction is negligible and radiative and conductive heat transfer modes dominate. For a pressure above  $5 \cdot 10^{-3}$  Pa, residual gas conduction represents the major contribution and the heat transfer through MLI increases significantly.

The influence of different parameters, such as number of layers, residual gas pressure and boundary temperature has been simulated by the mathematical model. For pressures below  $5 \cdot 10^{-3}$  Pa, it may occur that an increase of number of layers results in a heat flux rise, due to the variation of emissivity as a function of temperature. As a consequence for a critical value of outer layer temperature of 46 K, the function  $Q_{\text{rad}}$  reaches its maximum as shown in Figure 3a. Imposing the value of critical temperature to the outer layer, the mathematical model allowed to calculate the corresponding critical number of layers as a function of residual gas pressure (see Figure 3b)

Considering the same type of MLI shown in Figure 2b, the contribution of the three heat transfer modes has been calculated from layer to layer, as well as the heat transfer variation as a function of total number of layers (see Figure 4).

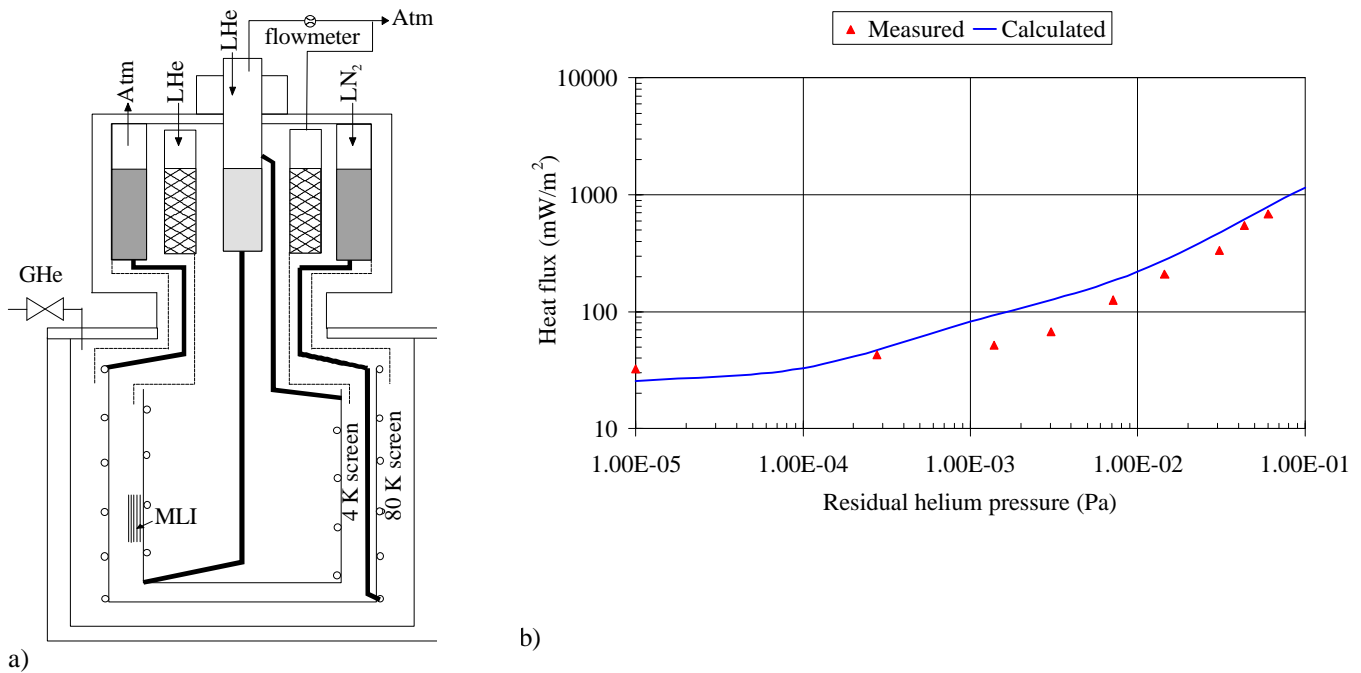
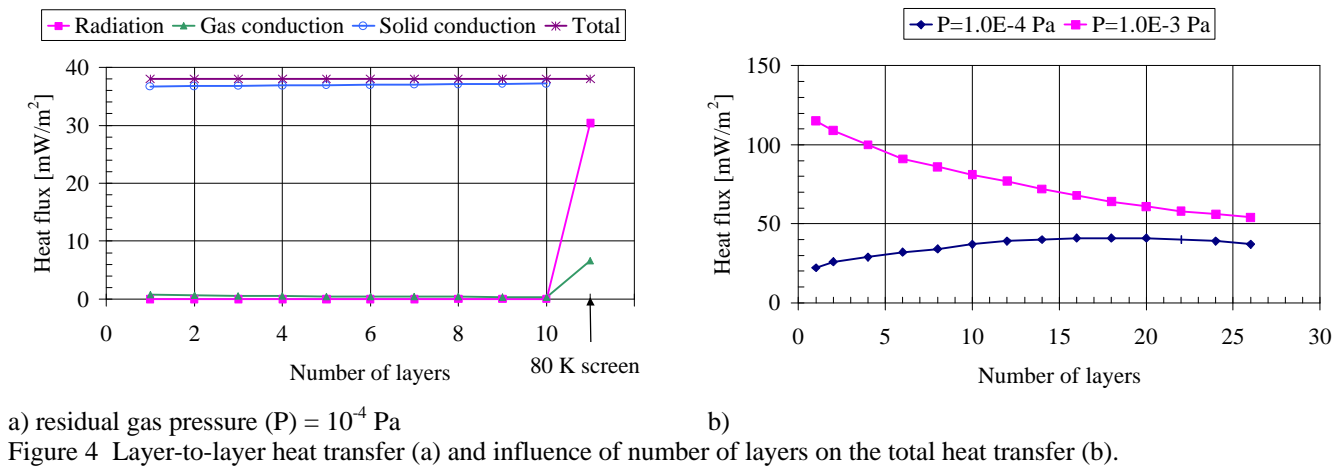
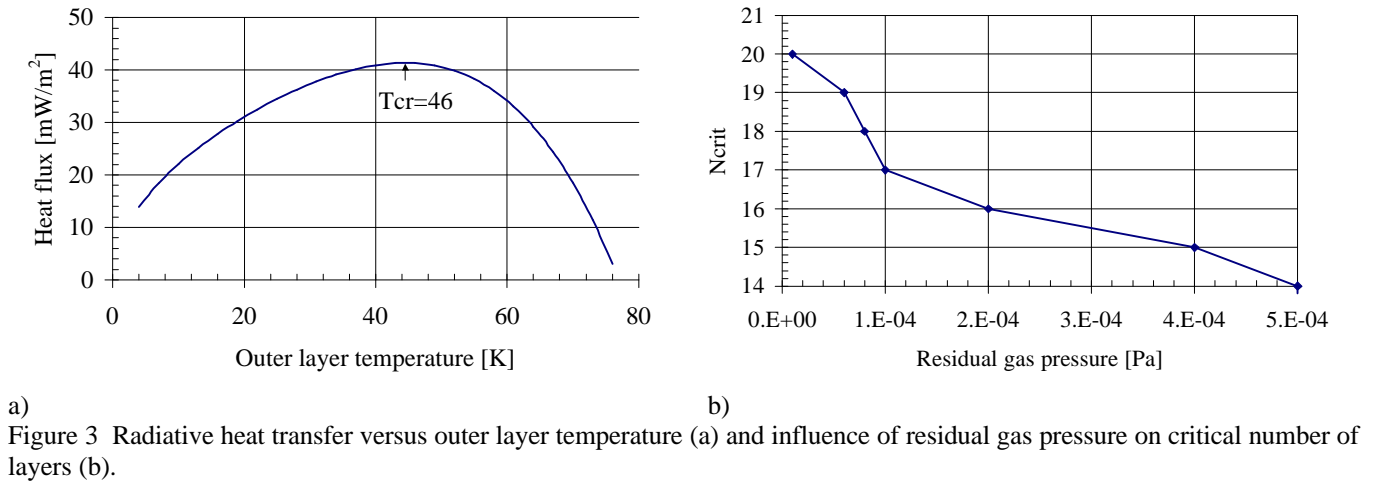


Figure 2 Experimental test facility at CERN (a) and comparison between experimental and calculated heat flux values (b)

## 5 CONCLUSION

A layer-to-layer model has been developed and revealed to be in a good agreement with experimental results obtained with a dedicated test facility built at CERN. The model enables to vary different parameters and investigate their influence on the MLI thermal performance. For residual gas pressures below  $5 \cdot 10^{-3}$  Pa, it is possible to define a number of layers which gives the highest value of radiation between the 80 K shield and the MLI outer layer. This can be explained by the combined effect of emissivity dependence on temperature ( $T^{0.5}$ ), and radiation from the 80 K shield to the outer MLI layer being proportional to  $T^4$ . At  $10^{-4}$  Pa the critical temperature of approximately 46 K is reached by implementing 17 layers and the corresponding heat flux from 80 K to 4 K results to be  $41 \text{ mW/m}^2$ .



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